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(54) **MEMS MULTI-AXIS ACCELEROMETER ELECTRODE STRUCTURE**

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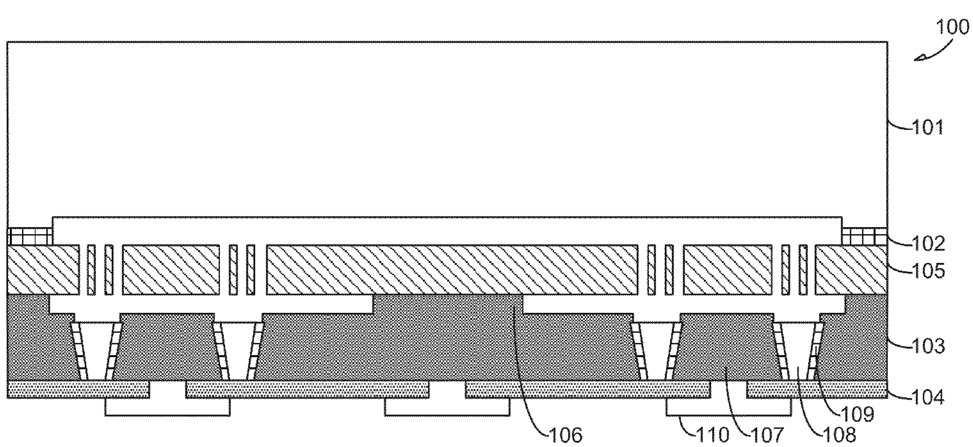
(57) **ABSTRACT**

This document discusses, among other things, an inertial sensor including a single proof-mass formed in an x-y plane of a device layer, the single proof-mass including a single, central anchor configured to suspend the single proof-mass above a via wafer. The inertial sensor further includes first and second electrode stator frames formed in the x-y plane of the device layer on respective first and second sides of the inertial sensor, the first and second electrode stator frames symmetric about the single, central anchor, and each separately including a central platform and an anchor configured to fix the central platform to the via wafer, wherein the anchors for the first and second electrode stator frames are asymmetric along the central platforms with respect to the single, central anchor.

17 Claims, 15 Drawing Sheets



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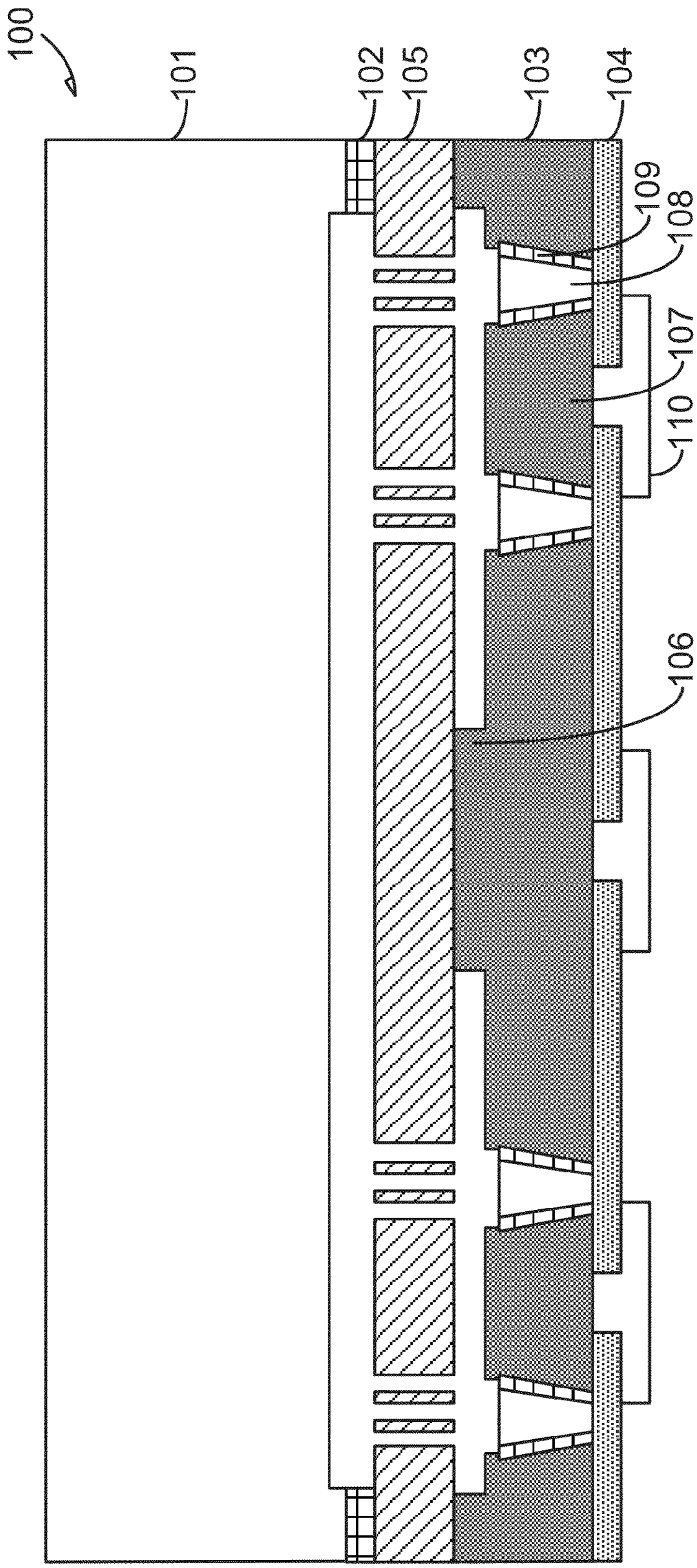

FIG. 1

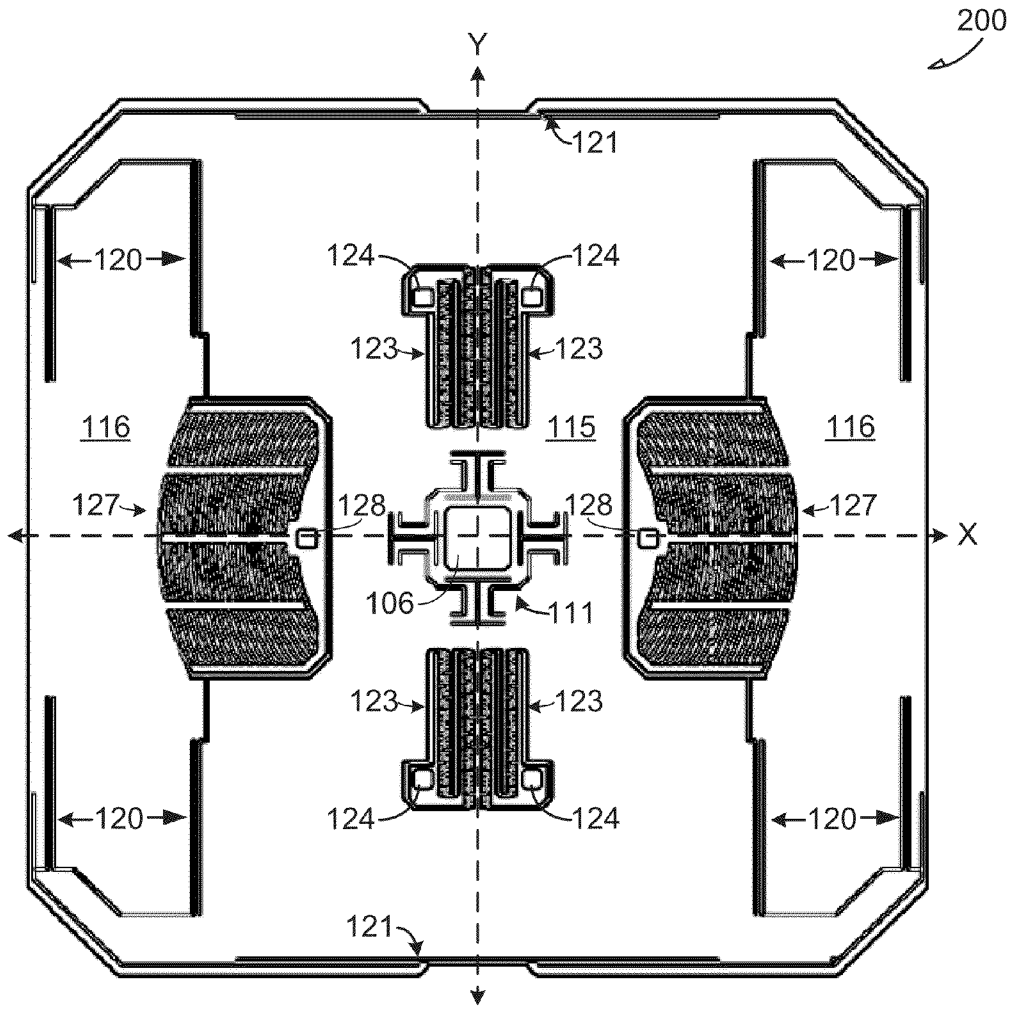
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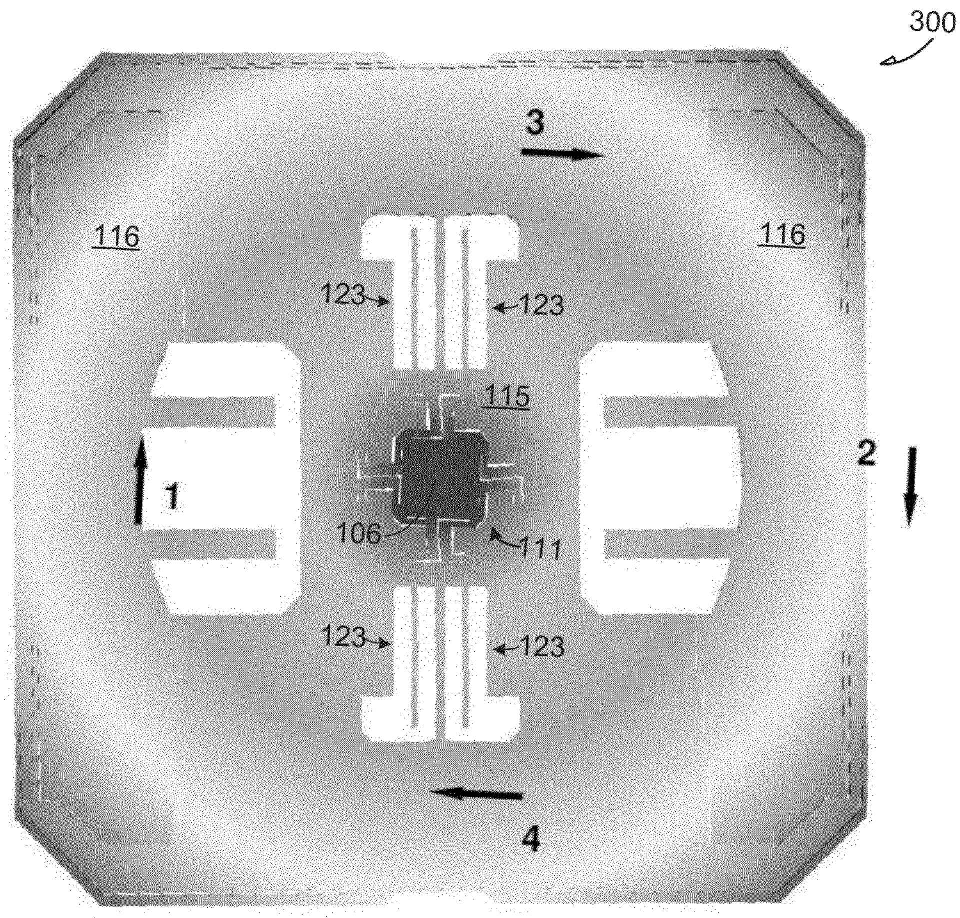
FIG. 2



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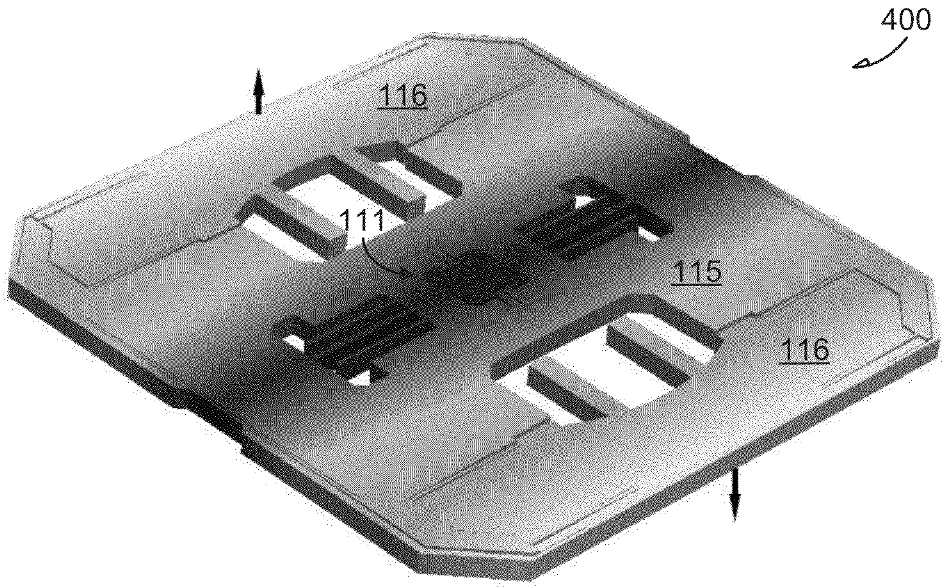

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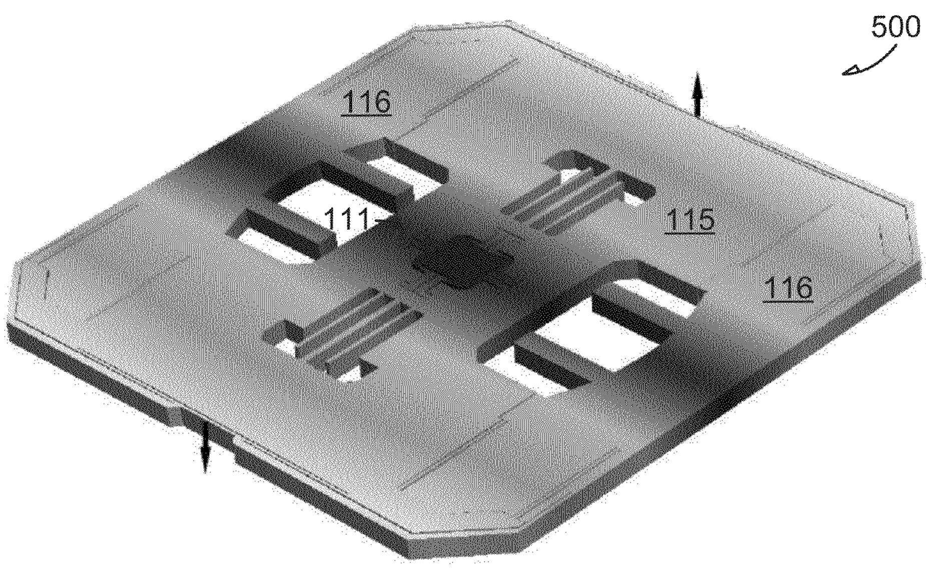

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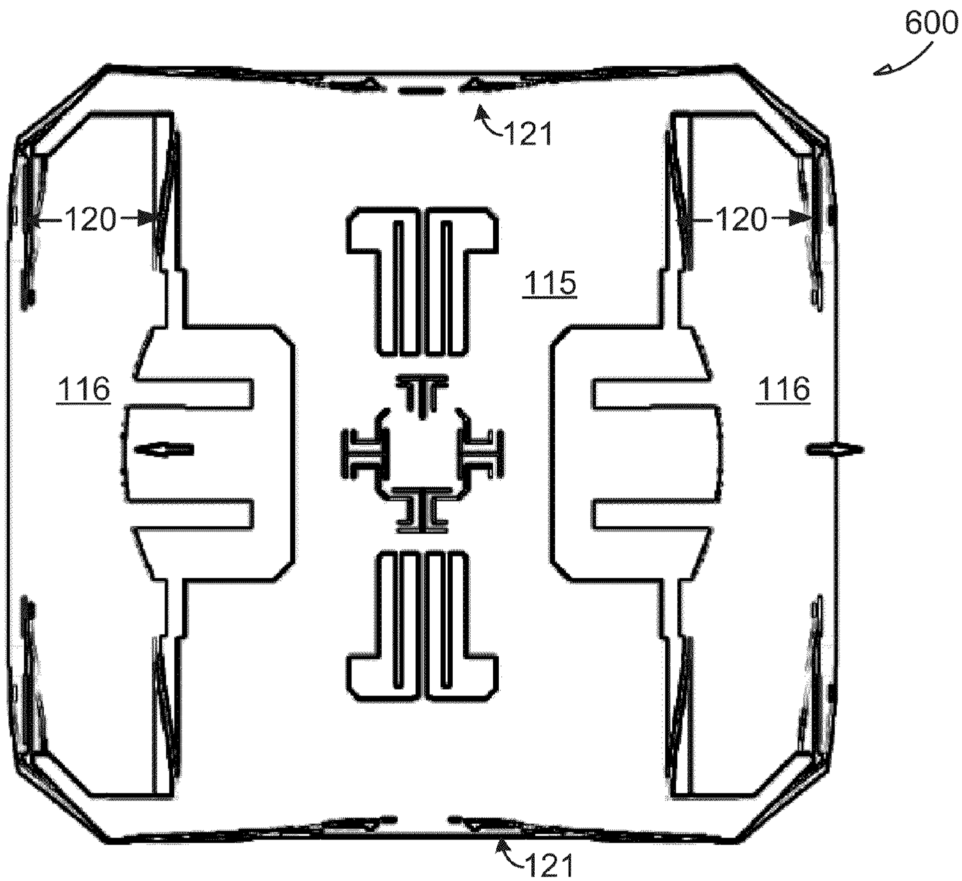

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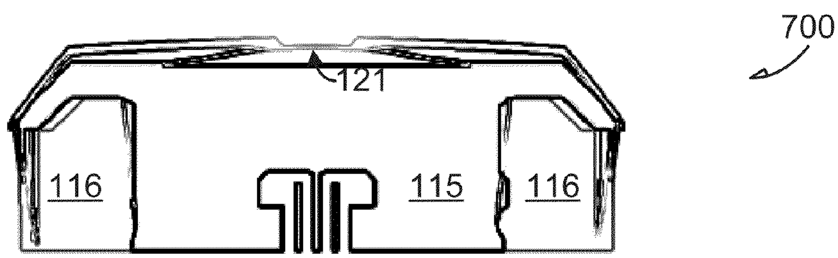

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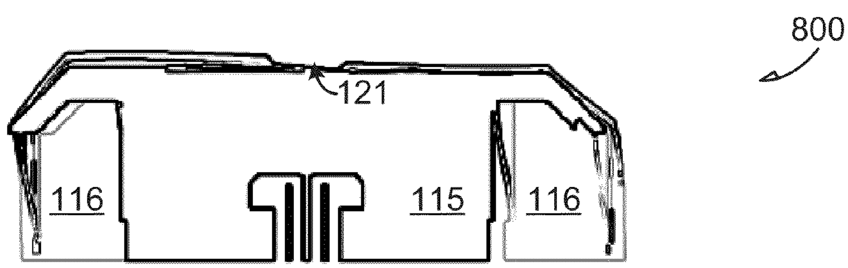

FIG. 8

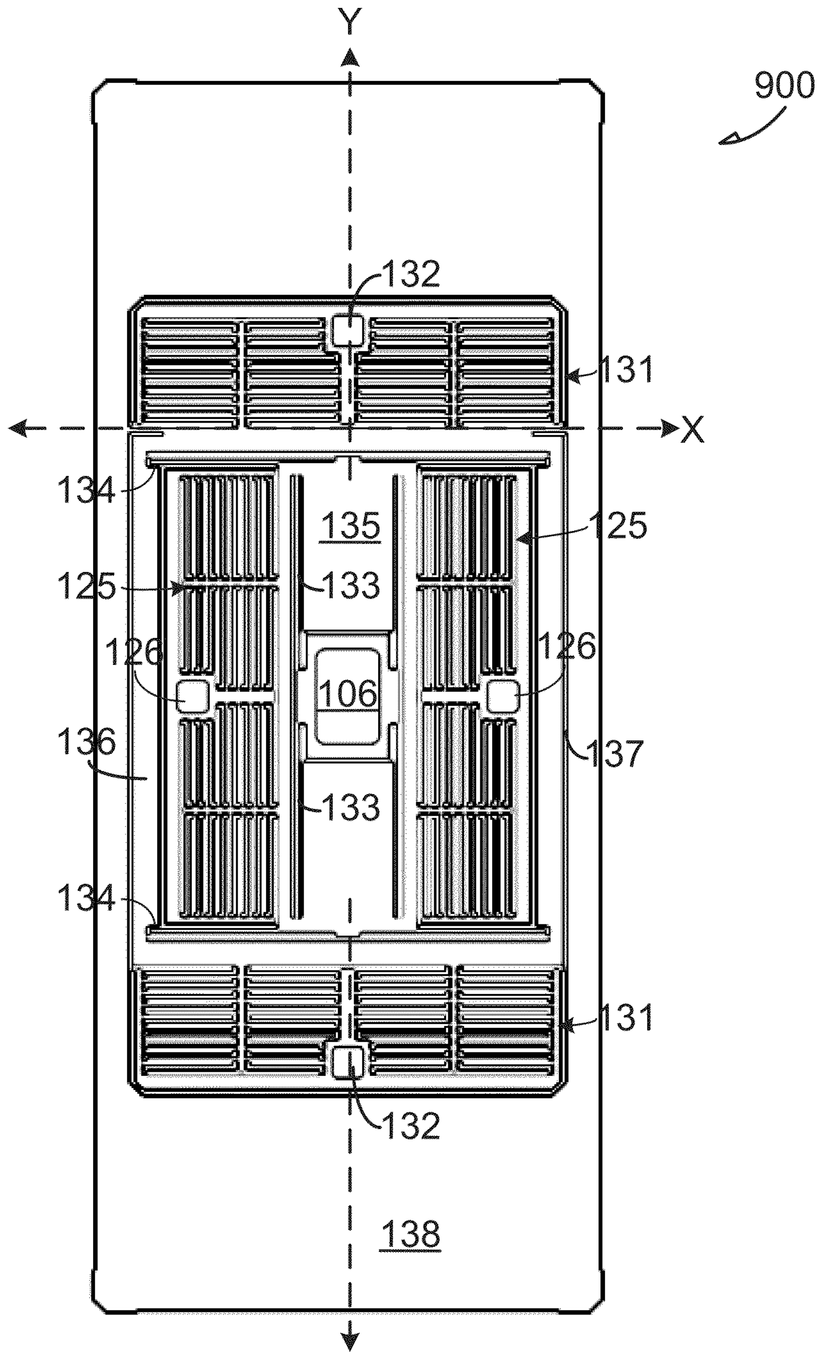
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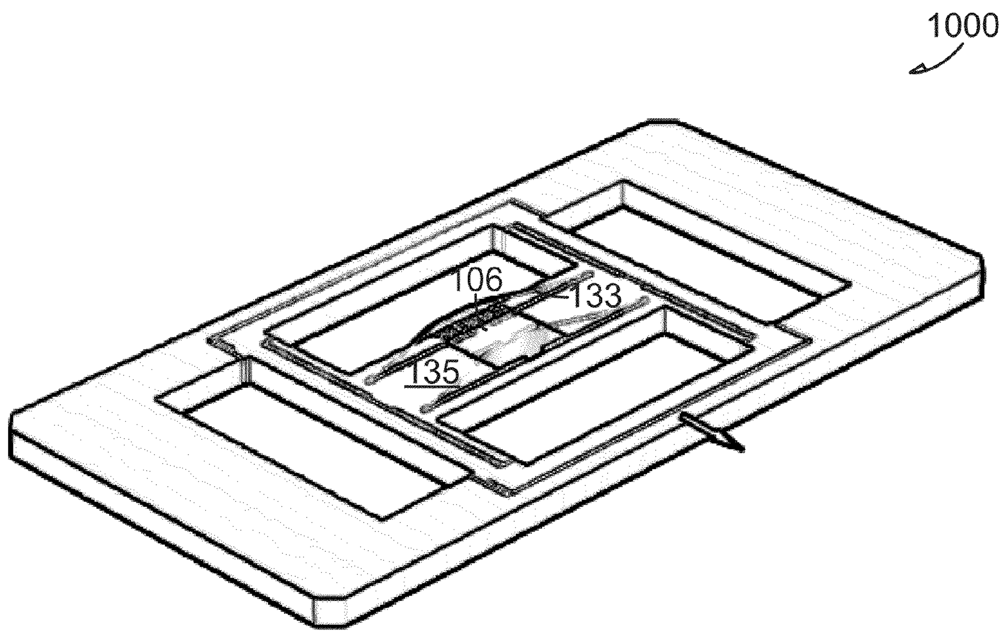
FIG. 9



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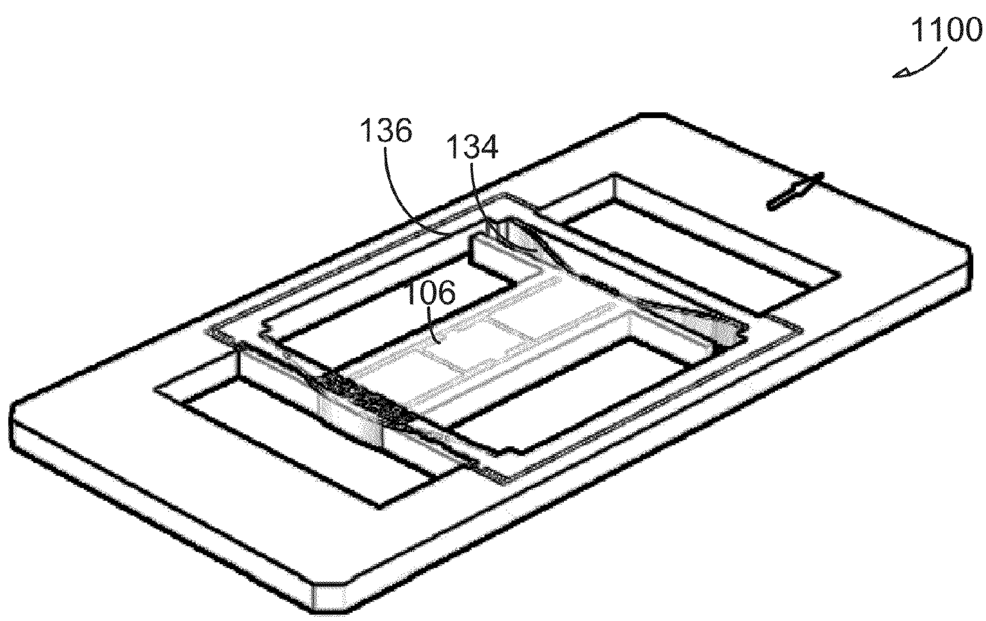

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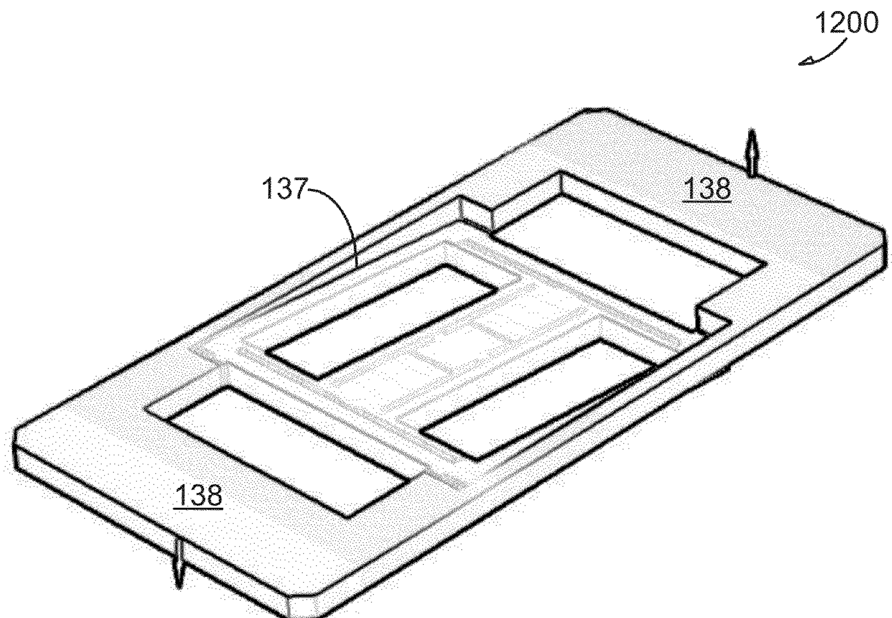

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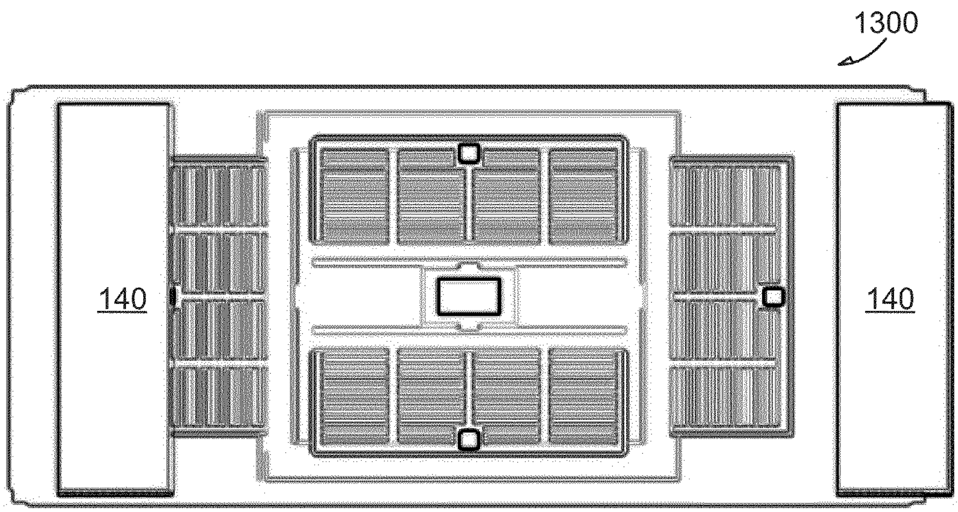
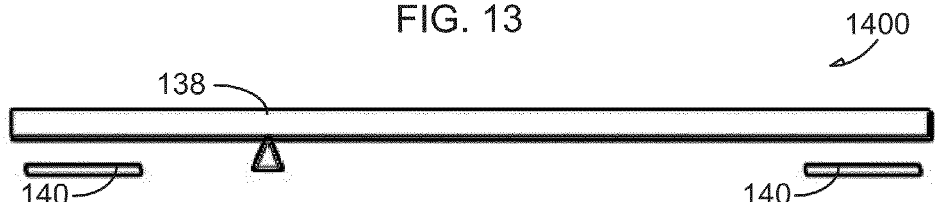


FIG. 13



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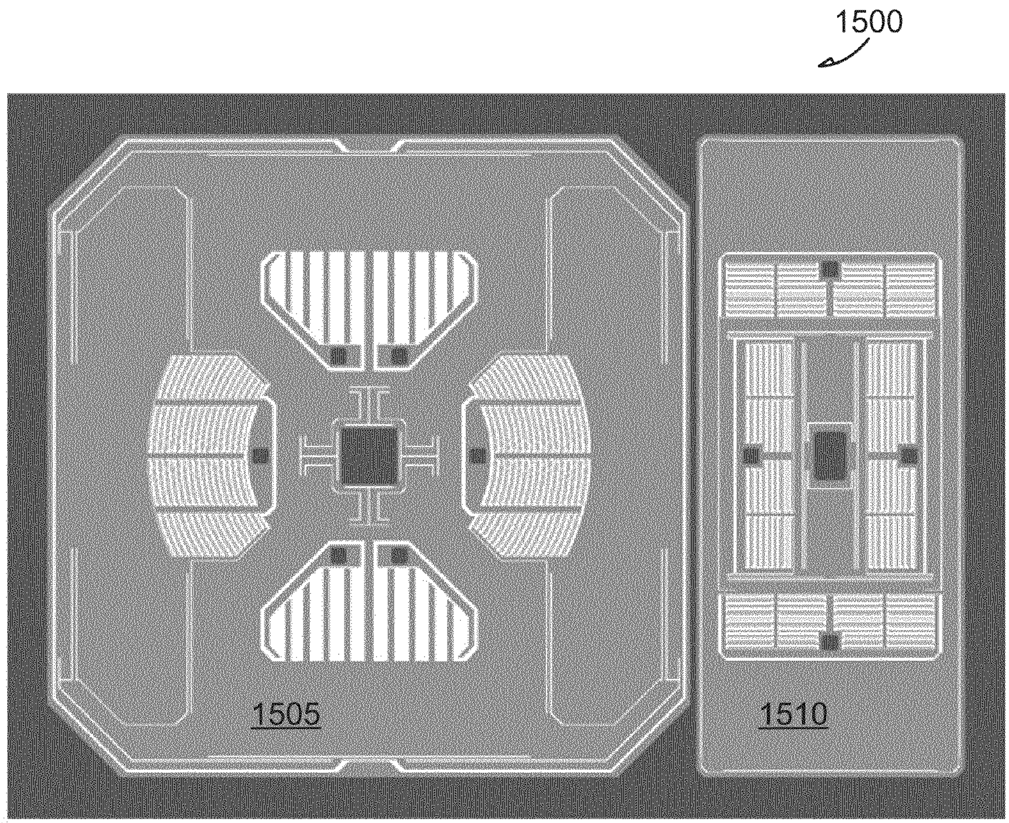


FIG. 15

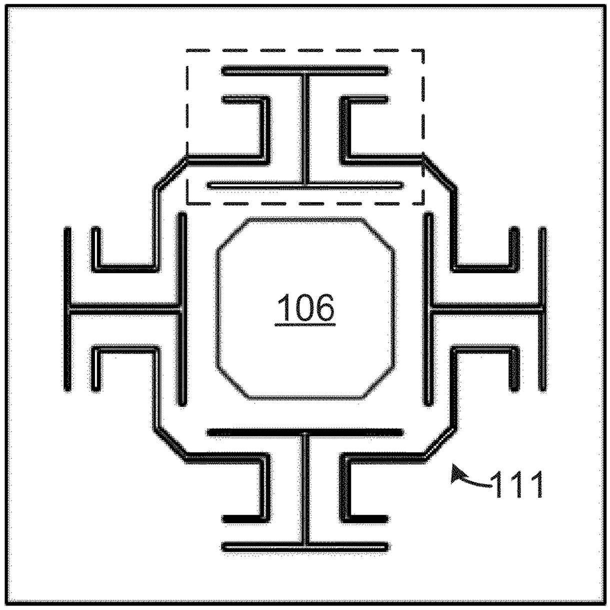


FIG. 16

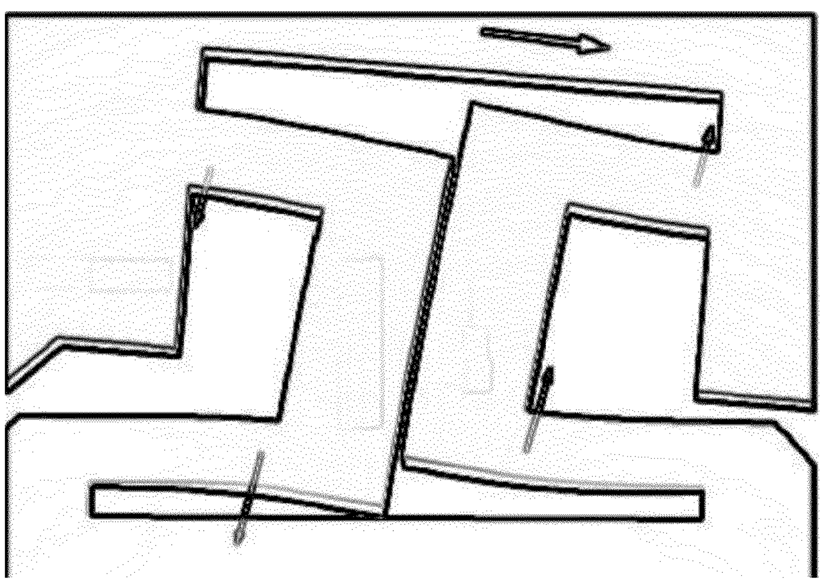
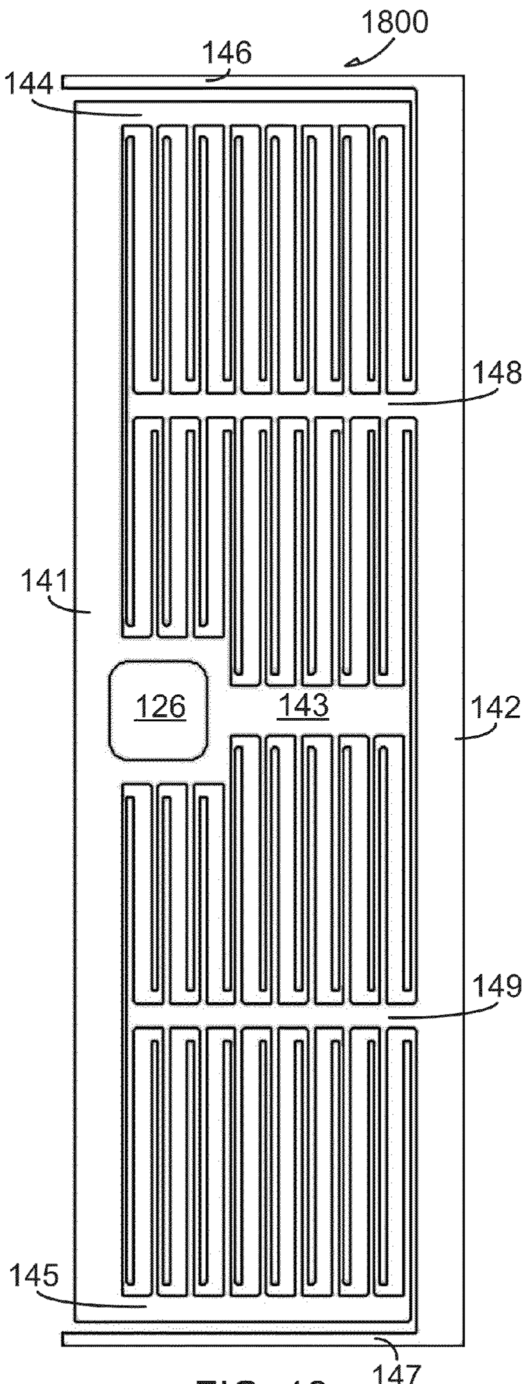


FIG. 17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147

FIG. 18

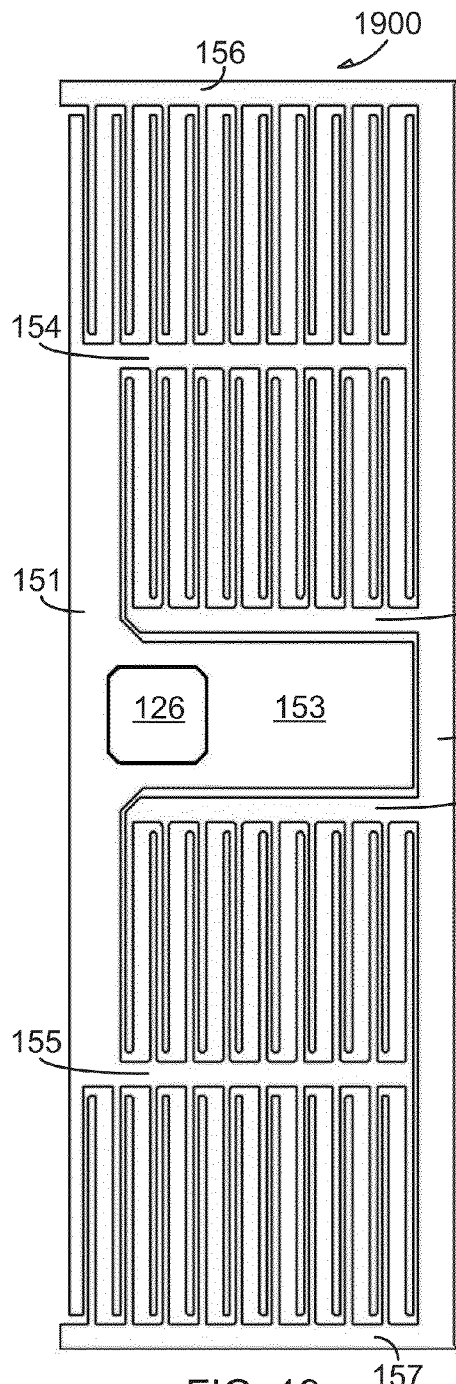
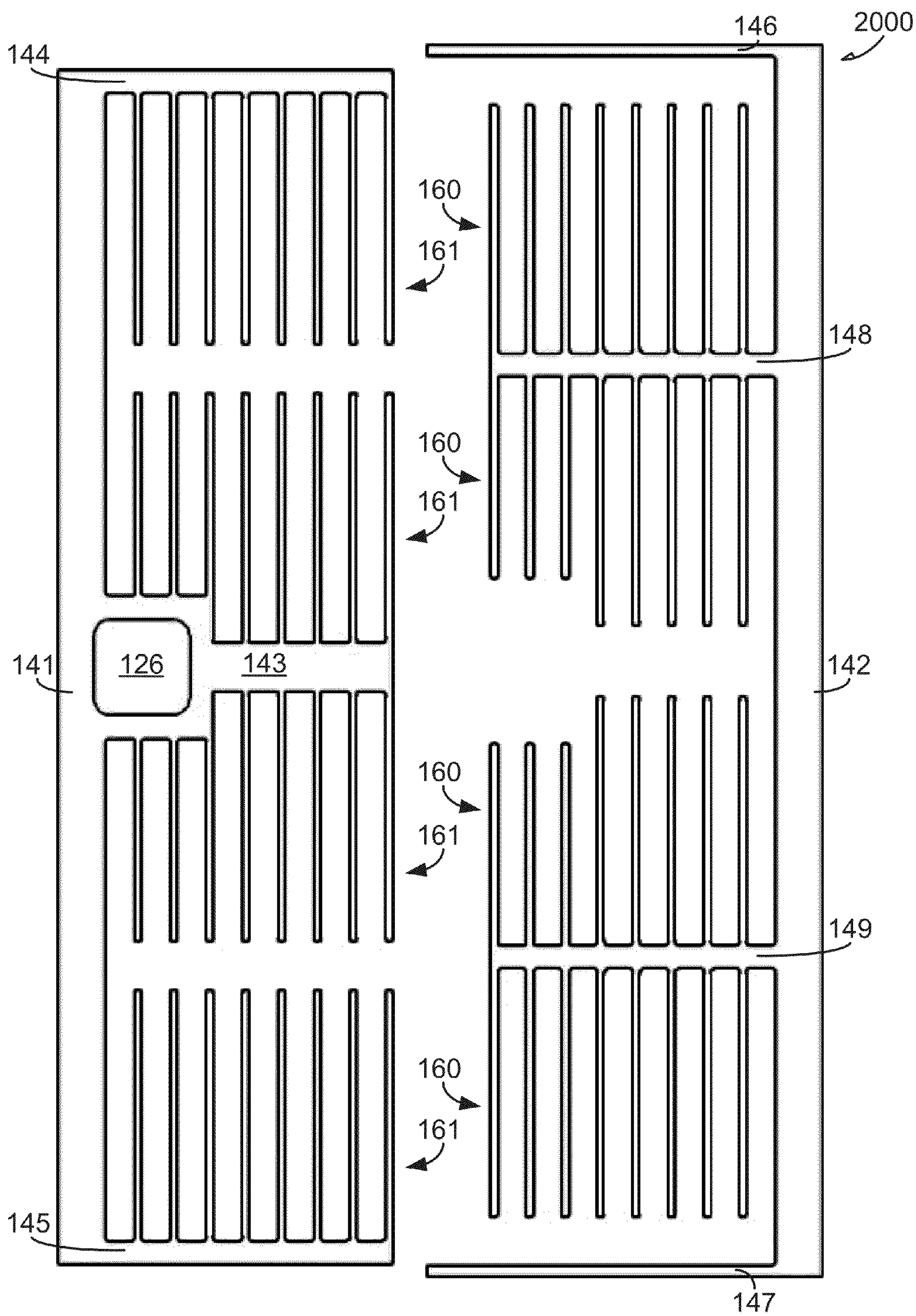

1900
156
154
151
158
126
153
152
159
155
157

FIG. 19



144
146
2000
160
161
148
160
161
141
126
143
142
160
161
149
160
161
145
147

FIG. 20

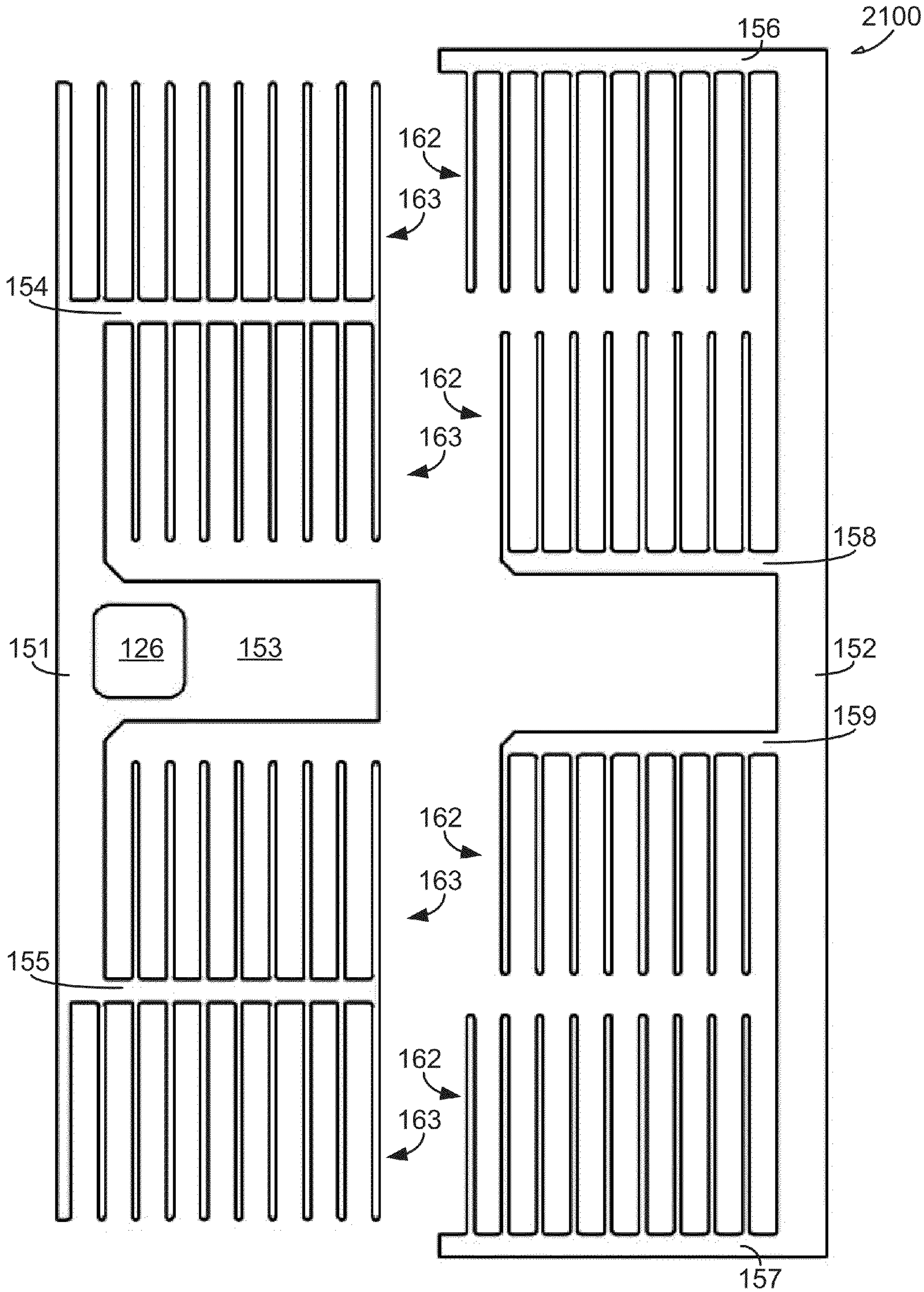

2100
156
162
163
154
162
163
158
151
126
153
152
159
162
163
155
162
163
157

FIG. 21

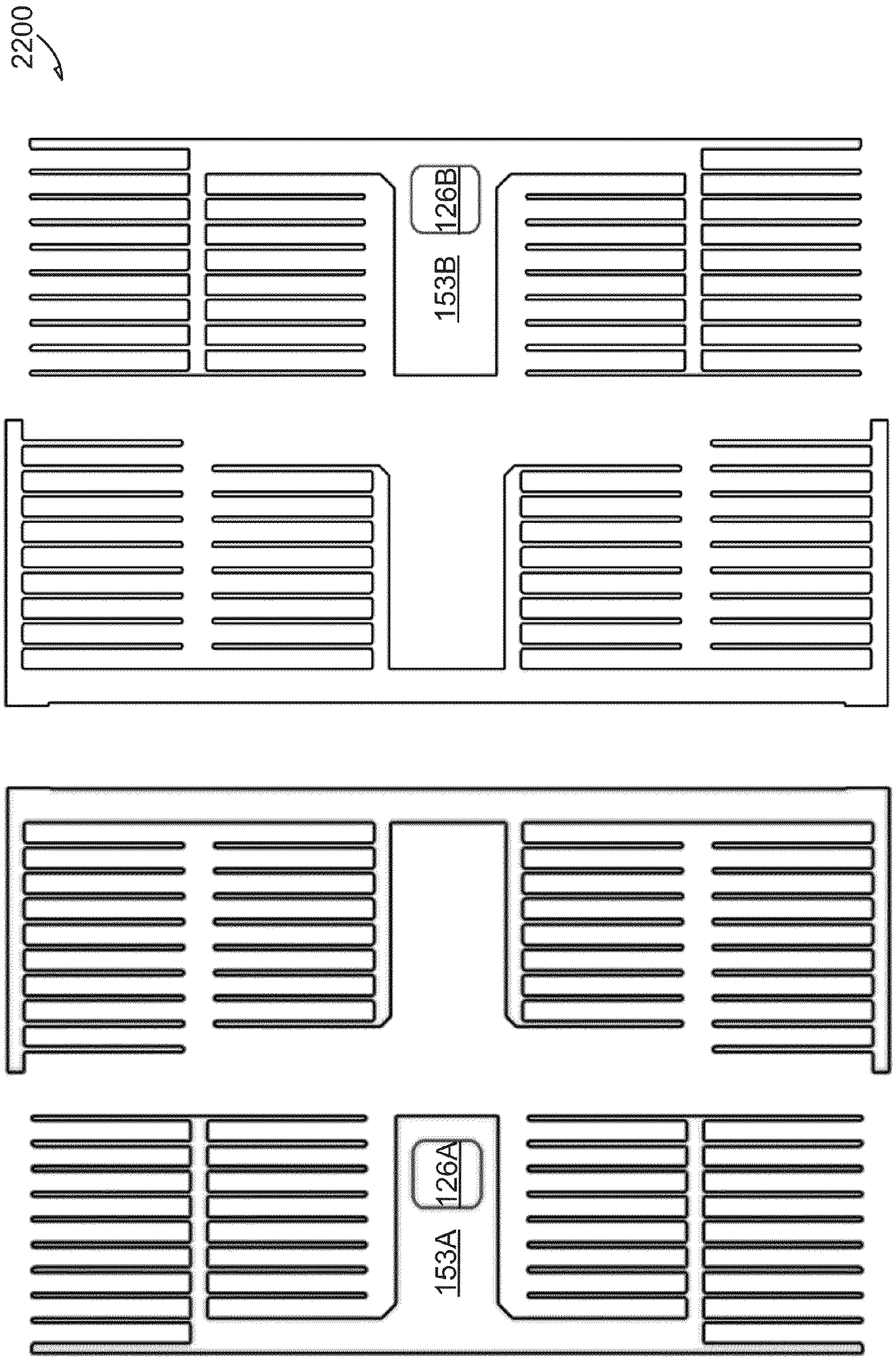


FIG. 22

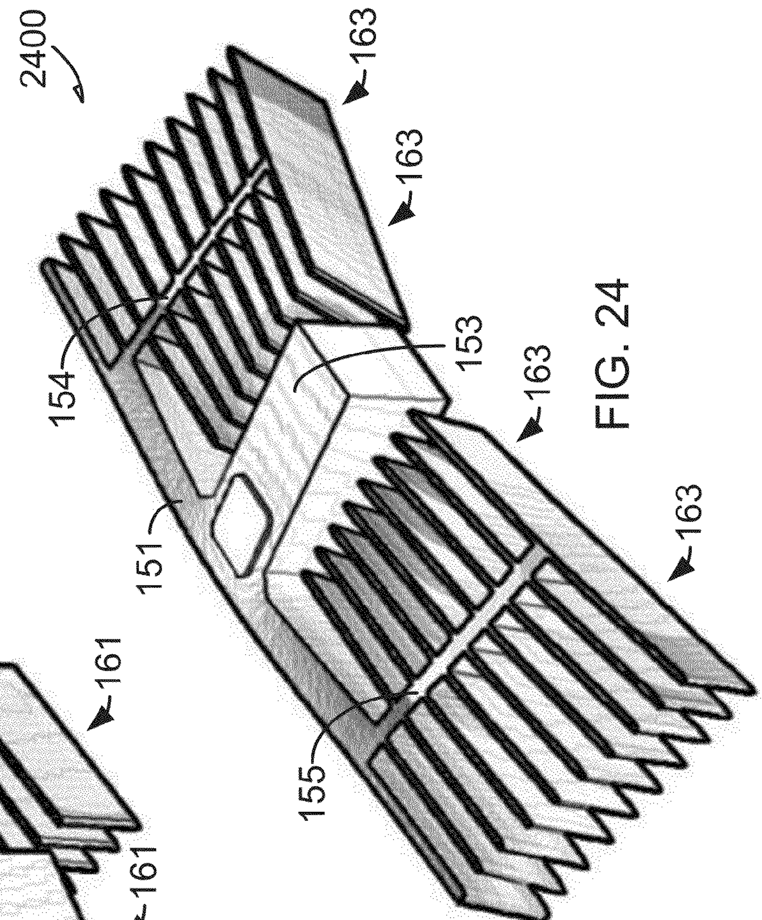

2400
163
163
153
163
154
151
163
155

FIG. 24

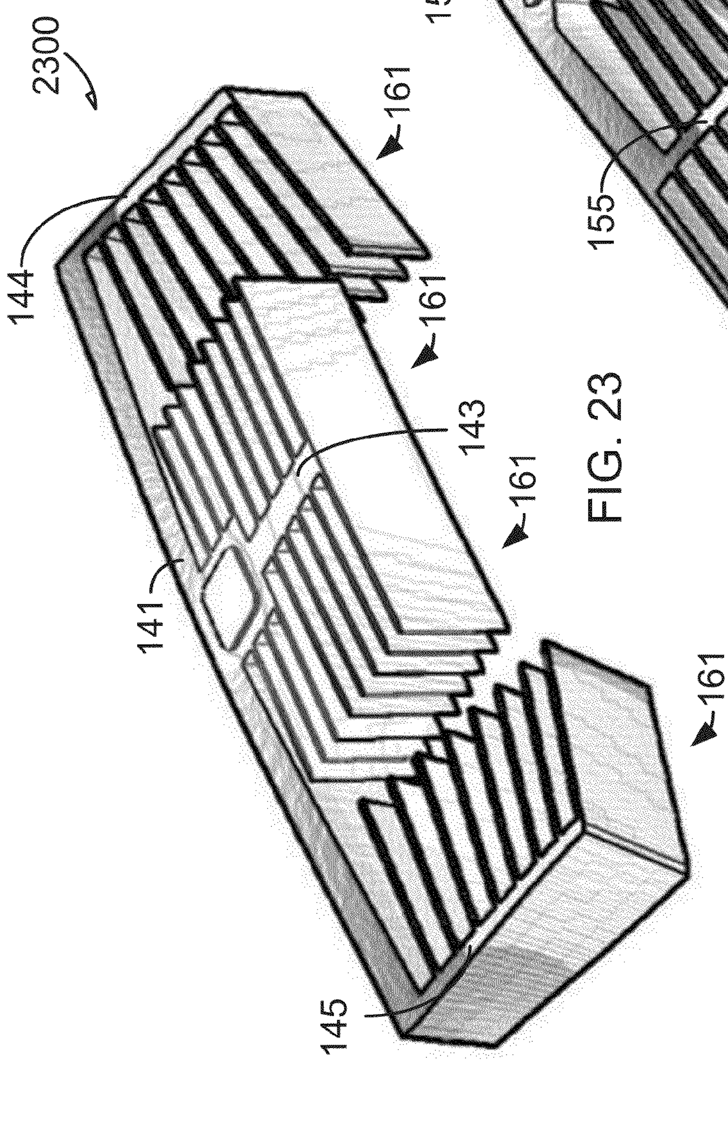

2300
161
144
161
143
161
141
161
145

FIG. 23

MEMS MULTI-AXIS ACCELEROMETER ELECTRODE STRUCTURE

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to Acar, International Application No. PCT/US2011/052065, entitled "MICROMACHINED MONOLITHIC 3-AXIS GYROSCOPE WITH SINGLE DRIVE," filed on Sep. 18, 2011, which claims the benefit of priority to Acar, U.S. Provisional Patent Application Ser. No. 61/384,245, entitled "MICROMACHINED MONOLITHIC 3-AXIS GYROSCOPE WITH SINGLE DRIVE," filed on Sep. 18, 2010, and to Acar, International Application No. PCT/US2011/052064, entitled "MICROMACHINED 3-AXIS ACCELEROMETER WITH A SINGLE PROOF-MASS," filed on Sep. 18, 2011, which claims the benefit of priority of Acar, U.S. Provisional Patent Application Ser. No. 61/384,246, entitled "MICROMACHINED 3-AXIS ACCELEROMETER WITH A SINGLE PROOF-MASS," filed on Sep. 18, 2010, each of which is hereby incorporated by reference herein in its entirety.

Further, this application is related to Acar et al., U.S. patent application Ser. No. 12/849,742, entitled "MICROMACHINED INERTIAL SENSOR DEVICES," filed on Aug. 3, 2010 and to Marx et al., U.S. patent application Ser. No. 12/849,787, entitled "MICROMACHINED DEVICES AND FABRICATING THE SAME," filed Aug. 3, 2010, each of which is hereby incorporated by reference herein in its entirety.

BACKGROUND

Several single-axis or multi-axis micromachined gyroscope structures have been integrated into a system to form a 3-axis gyroscope cluster. However, the size and cost of such clusters consisting of separate sensors can be excessive for certain applications. Even though single or multi-axis gyroscopes can be fabricated on a single MEMS chip, separate drive and sense electronics are required for each sensor. Further, the demand for three axis acceleration detection in consumer/mobile, automotive and aerospace/defense applications is constantly increasing. Many single-axis or multi-axis micromachined accelerometer structures have utilized separate proof-masses for each acceleration axis.

OVERVIEW

This document discusses, among other things, an inertial sensor including a single proof-mass formed in an x-y plane of a device layer, the single proof-mass including a single, central anchor configured to suspend the single proof-mass above a via wafer. The inertial sensor further includes first and second electrode stator frames formed in the x-y plane of the device layer on respective first and second sides of the inertial sensor, the first and second electrode stator frames symmetric about the single, central anchor, and each separately including a central platform and an anchor configured to fix the central platform to the via wafer, wherein the anchors for the first and second electrode stator frames are asymmetric along the central platforms with respect to the single, central anchor.

This overview is intended to provide an overview of subject matter of the present patent application. It is not intended to provide an exclusive or exhaustive explanation of the invention. The detailed description is included to provide further information about the present patent application.

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, which are not necessarily drawn to scale, like numerals may describe similar components in different views. Like numerals having different letter suffixes may represent different instances of similar components. The drawings illustrate generally, by way of example, but not by way of limitation, various embodiments discussed in the present document.

FIG. **1** illustrates generally a schematic cross sectional view of a 3-degrees-of-freedom (3-DOF) inertial measurement unit (IMU).

FIG. **2** illustrates generally an example of a 3-axis gyroscope.

FIG. **3** illustrates generally an example of a 3-axis gyroscope in drive motion.

FIG. **4** illustrates generally an example of a 3-axis gyroscope including a single proof-mass during sense motion in response to rotation about the x-axis.

FIG. **5** illustrates generally an example of a 3-axis gyroscope including a single proof-mass during sense motion in response to rotation about the y-axis.

FIG. **6** illustrates generally an example of a 3-axis gyroscope including a single proof-mass during sense motion in response to rotation about the z-axis.

FIGS. **7** and **8** illustrate generally examples of a 3-axis gyroscope including a z-axis gyroscope coupling flexure bearing during anti-phase motion and in-phase motion, respectively.

FIG. **9** illustrates generally an example of a 3-axis accelerometer.

FIG. **10** illustrates generally an example of a 3-axis accelerometer in sense motion in response to an x-axis acceleration.

FIG. **11** illustrates generally an example of a 3-axis accelerometer in sense motion in response to a y-axis acceleration.

FIG. **12** illustrates generally an example of a 3-axis accelerometer in sense motion in response to a z-axis acceleration.

FIG. **13** illustrates generally an example of a system including via wafer electrode placement.

FIG. **14** illustrates generally an example side view of a 3-axis accelerometer including a single proof-mass.

FIG. **15** illustrates generally an example of a 3+3-degrees-of-freedom (3+3DOF) inertial measurement unit (IMU).

FIG. **16** illustrates generally an example of the central suspension at rest about an anchor.

FIG. **17** illustrates generally an example of a portion of the central suspension in drive motion.

FIGS. **18**-**22** illustrate generally examples of an accelerometer electrode structures.

FIGS. **23** and **24** illustrate generally examples of the lowest out-of-plane resonant mode of electrode stator frames.

DETAILED DESCRIPTION

The present inventors have recognized, among other things, a micromachined monolithic 3-axis gyroscope configured to utilize a single center-anchored proof-mass to detect angular rate about all three axes while effectively decoupling the response modes for each axis to minimize cross-axis sensitivity.

In an example, the unique proof-mass partitioning and flexure structure disclosed herein can allow 3-axis angular rate detection utilizing a single drive-mode oscillation, which can require only one drive control loop for all axes. Thus, in contrast to existing multi-axis gyroscopes that use three separate drive loops, complexity and cost of control electronics of the 3-axis gyroscope disclosed herein can be significantly reduced.

Further, the present inventors have recognized, among other things, a micromachined 3-axis accelerometer configured to utilize a single center-anchored proof-mass to detect accelerations about all three axes while effectively decoupling the response modes for each axis to minimize cross-axis sensitivity.

In an example, the unique proof-mass and flexure structure disclosed herein can allow 3-axis acceleration detection using a single center anchored proof-mass. Thus, in contrast to existing multi-axis accelerometers that utilize separate proof-masses for each acceleration axis, the overall die size and the total cost of the microelectromechanical system (MEMS) sensing element of the 3-axis accelerometer disclosed herein can be significantly reduced.

Further, as die deformation and packaging stress affect the temperature coefficients of the MEMS sensors, and further, as one or more of the sensors disclosed herein may not be centered on the die, the present inventors have recognized, among other things, that shifting mass from an electrode stator frame to a proof mass frame can positively affect performance (e.g., more robust, improved shock and vibration resistance, etc.). Moreover, widening the anchor platform of the electrode stator frame can allow for independent or asymmetric placement of the electrode stator frame anchors, which can, among other things, improve temperature performance of the inertial sensor.

Device Structure

FIG. **1** illustrates generally a schematic cross sectional view of a 3-degrees-of-freedom (3-DOF) inertial measurement unit (IMU) **100**, such as a 3-DOF gyroscope or a 3-DOF micromachined accelerometer, formed in a chip-scale package including a cap wafer **101**, a device layer **105** including micromachined structures (e.g., a micromachined 3-DOF IMU), and a via wafer **103**. In an example, the device layer **105** can be sandwiched between the cap wafer **101** and the via wafer **103**, and the cavity between the device layer **105** and the cap wafer **101** can be sealed under vacuum at the wafer level.

In an example, the cap wafer **101** can be bonded to the device layer **105**, such as using a metal bond **102**. The metal bond **102** can include a fusion bond, such as a non-high temperature fusion bond, to allow getter to maintain long term vacuum and application of anti-stiction coating to prevent stiction that can occur to low-g acceleration sensors. In an example, during operation of the device layer **105**, the metal bond **102** can generate thermal stress between the cap wafer **101** and the device layer **105**. In certain examples, one or more features can be added to the device layer **105** to isolate the micromachined structures in the device layer **105** from thermal stress, such as one or more stress reducing grooves formed around the perimeter of the micromachined structures. In an example, the via wafer **103** can be bonded to the device layer **105**, such as fusion bonded (e.g., silicon-silicon fusion bonded, etc.), to obviate thermal stress between the via wafer **103** and the device layer **105**.

In an example, the via wafer **103** can include one or more isolated regions, such as a first isolated region **107**, isolated from one or more other regions of the via wafer **103**, for example, using one or more through-silicon-vias (TSVs), such as a first TSV **108** insulated from the via wafer **103** using a dielectric material **109**. In certain examples, the one or more isolated regions can be utilized as electrodes to sense or actuate out-of-plane operation modes of the 6-axis inertial sensor, and the one or more TSVs can be configured to provide electrical connections from the device layer **105** outside of the system **100**. Further, the via wafer **103** can include one or more contacts, such as a first contact **110**, selectively isolated from one or more portions of the via wafer **103** using a dielectric layer **104** and configured to provide an electrical connection between one or more of the isolated regions or TSVs of the via wafer **103** to one or more external components, such as an ASIC wafer, using bumps, wire bonds, or one or more other electrical connection. In certain examples, the 3-degrees-of-freedom (3-DOF) gyroscope or the micromachined accelerometer in the device layer **105** can be supported or anchored to the via wafer **103** by bonding the device layer **105** to a protruding portion of the via wafer **103**, such as an anchor **106**. In an example, the anchor **106** can be located substantially at the center of the via wafer **103**, and the device layer **105** can be fusion bonded to the anchor **106**, such as to eliminate problems associated with metal fatigue.

Gyroscope Device Structure

FIG. **2** illustrates generally an example of a 3-axis gyroscope **200**, such as formed in a single plane of a device layer **105** of a 3-DOF IMU **100**. In an example, the structure of the 3-axis gyroscope **200** can be symmetric about the x and y axes illustrated in FIG. **2**, with a z-axis conceptually coming out of the figure. Reference in FIG. **2** is made to structure and features in one portion of the 3-axis gyroscope **200**. However, in certain examples, such reference and description can apply to unlabeled like portions of the 3-axis gyroscope **200**.

In an example, the 3-axis gyroscope **200** can include a single proof-mass design providing 3-axis gyroscope operational modes patterned into the device layer **105** of the 3-DOF IMU **100**, such as illustrated in the example of FIG. **1**.

In an example, the single proof-mass can be suspended at its center using a single central anchor (e.g., anchor **106**) and a central suspension **111** including symmetric central flexure bearings ("flexures"), such as disclosed in the copending Acar et al., PCT Patent Application Serial No. US2011052006, entitled "FLEXURE BEARING TO REDUCE QUADRATURE FOR RESONATING MICROMACHINED DEVICES," filed on Sep. 16, 2011, which is hereby incorporated by reference in its entirety. The central suspension **111** can allow the single proof-mass to oscillate torsionally about the x, y, and z axes, providing three gyroscope operational modes, including:

(1) Torsional in-plane drive motion about the z-axis (e.g., as illustrated in FIG. **3**);

(2) Torsional out-of-plane y-axis gyroscope sense motion about the x-axis (e.g., as illustrated in FIG. **4**); and

(3) Torsional out-of-plane x-axis gyroscope sense motion about the y-axis (e.g., as illustrated in FIG. **5**).

Further, the single proof-mass design can be composed of multiple sections, including, for example, a main proof-mass section **115** and x-axis proof-mass sections **116** symmetric about the y-axis. In an example, drive electrodes **123** can be placed along the y-axis of the main proof-mass section **115**. In combination with the central suspension **111**, the drive electrodes **123** can be configured to provide a torsional in-plane drive motion about the z-axis, allowing detection of angular motion about the x and y axes.

In an example, the x-axis proof-mass sections **116** can be coupled to the main proof-mass section **115** using z-axis gyroscope flexure bearings **120**. In an example, the z-axis gyroscope flexure bearings **120** can allow the x-axis proof-mass sections **116** to oscillate linear anti-phase in the x-direction for the z-axis gyroscope sense motion.

Further, the 3-axis inertial sensor **200** can include z-axis gyroscope sense electrodes **127** configured to detect anti-phase, in-plane motion of the x-axis proof-mass sections **116** along the x-axis.

In an example, each of the drive electrodes **123** and z-axis gyroscope sense electrodes **127** can include moving fingers coupled to one or more proof-mass sections interdigitated with a set of stationary fingers fixed in position (e.g., to the via wafer **103**) using a respective anchor, such as anchors **124**, **128**.

Gyroscope Operational Modes

FIG. **3** illustrates generally an example of a 3-axis gyroscope **300** in drive motion. In an example, the drive electrodes **123** can include a set of moving fingers coupled to the main proof-mass section **115** interdigitated with a set of stationary fingers fixed in position using a first drive anchor **124** (e.g., a raised and electrically isolated portion of the via wafer **103**). In an example, the stationary fingers can be configured to receive energy through the first drive anchor **124**, and the interaction between the interdigitated moving and stationary fingers of the drive electrodes **123** can be configured to provide an angular force to the single proof-mass about the z-axis.

In the example of FIG. **3**, the drive electrodes **123** are driven to rotate the single proof-mass about the z-axis while the central suspension **111** provides restoring torque with respect to the fixed anchor **106**, causing the single proof-mass to oscillate torsionally, in-plane about the z-axis at a drive frequency dependent on the energy applied to the drive electrodes **123**. In certain examples, the drive motion of the single proof-mass can be detected using the drive electrodes **123**.

X-Axis Rate Response

FIG. **4** illustrates generally an example of a 3-axis gyroscope **400** including a single proof-mass during sense motion in response to rotation about the x-axis, the single proof-mass including a main proof-mass section **115**, x-axis proof-mass sections **116**, and central suspension **111**.

In the presence of an angular rate about the x-axis, and in conjunction with the drive motion of the 3-axis gyroscope **400** described in the example of FIG. **3**, Coriolis forces in opposite directions along the z-axis can be induced on the x-axis proof-mass sections **116** because the velocity vectors are in opposite directions along the y-axis. Thus, the single proof-mass can be excited torsionally about the y-axis by flexing the central suspension **111**. The sense response can be detected using out-of-plane x-axis gyroscope sense electrodes, e.g., formed in the via wafer **103** and using capacitive coupling of the x-axis proof-mass sections **116** and the via wafer **103**.

Y-Axis Rate Response

FIG. **5** illustrates generally an example of a 3-axis gyroscope **500** including a single proof-mass during sense motion in response to rotation about the y-axis, the single proof-mass including a main proof-mass section **115**, x-axis proof-mass sections **116**, and central suspension **111**.

In the presence of an angular rate about the y-axis, and in conjunction with the drive motion of the 3-axis gyroscope **400** described in the example of FIG. **3**, Coriolis forces in opposite directions along the z-axis can be induced on the main proof-mass section **115** because the velocity vectors are in opposite directions along the x-axis. Thus, the single proof-mass can be excited torsionally about the x-axis by flexing the central suspension **111**. The sense response can be detected using out-of-plane y-axis gyroscope sense electrodes, e.g., formed in the via wafer **103** and using capacitive coupling of the main proof-mass section **115** and the via wafer **103**.

Z-Axis Rate Response

FIG. **6** illustrates generally an example of a 3-axis gyroscope **600** including a single proof-mass during sense motion in response to rotation about the z-axis, the single proof-mass including a main proof-mass section **115**, x-axis proof-mass sections **116**, central suspension, z-axis flexure bearings **120**, and z-axis gyroscope coupling flexure bearings **121**.

In the presence of an angular rate about the z-axis, and in conjunction with the drive motion of the 6-axis inertial sensor **400** described in the example of FIG. **3**, Coriolis forces in opposite directions along the x-axis can be induced on the x-axis proof-mass sections **116** because the velocity vectors are in opposite directions along the y-axis. Thus, the x-axis proof-mass sections **116** can be excited linearly in opposite directions along the x-axis by flexing the z-axis flexure bearings **120** in the x-direction. Further, the z-axis gyroscope coupling flexure bearings **121** can be used to provide a linear anti-phase resonant mode of the x-axis proof-mass sections **116**, which are directly driven by the anti-phase Coriolis forces. The sense response can be detected using in-plane parallel-plate sense electrodes, such as the z-axis gyroscope sense electrodes **127** formed in the device layer **105**.

FIGS. **7** and **8** illustrate generally examples of a 3-axis gyroscope **700** including a z-axis gyroscope coupling flexure bearing **121** during anti-phase motion and in-phase motion, respectively. To improve the vibration rejection of the 3-axis gyroscope **700** due to x-axis acceleration, the z-axis gyroscope coupling flexure bearings **121** is configured to suppress in-phase motion of the x-axis proof-mass sections **116**.

During the anti-phase motion, the connection beams that connect the two x-axis proof-mass sections **116** to the z-axis gyroscope coupling flexure bearing **121** apply forces in the same direction and the coupling beams undergo a natural bending with low stiffness.

In contrast, during the in-phase motion, the coupling beams of the z-axis gyroscope coupling flexure bearing **121** apply forces in opposite directions on the coupling beams, forcing the coupling beams into a twisting motion with a higher stiffness. Thus, the in-phase motion stiffness and the resonant frequencies are increased, providing better vibration rejection.

Accelerometer Device Structure

FIG. **9** illustrates generally an example of a 3-axis accelerometer **900**, such as formed in a single plane of a device layer **105** of a 3-DOF IMU **100**. In an example, the 3-axis accelerometer **900** can include a single proof-mass design, providing 3-axis accelerometer operational modes patterned into the device layer **105** of the 3-DOF IMU **100**, such as illustrated in the example of FIG. **1**.

In an example, the single proof-mass can be suspended at its center to a single central anchor (e.g., anchor **106**) using a series of flexure bearings and frames that aim to decouple the response modes and reduce cross-axis sensitivities. In an example, the 3-axis accelerometer **900** can include x-axis flexure bearings **133** configured to couple the anchor **106** to the x-axis frame **135** and allow the x-axis frame **135** to deflect in response to acceleration along the x-axis. Further, the device can include y-axis flexure bearings **134** configured to couple the x-axis frame **135** to the y-axis frame **136** and allow the y-axis frame **136** to deflect with respect to the x-axis frame **135** in response to accelerations along the y-axis, and z-axis flexure bearings **137** configured to couple the y-axis frame **136** to the remainder of the proof-mass **138**. The z-axis flexure bearings **137** function as a torsional hinge, allowing the proof-mass to deflect torsionally out-of-plane about the axis that passes through the center of the beams.

Further, the 3-axis accelerometer **900** can include x-axis accelerometer sense electrodes **125** configured to detect in-phase, in-plane x-axis motion of the x-axis frame **135**, or y-axis accelerometer sense electrodes **131** configured to detect in-phase, in-plane, y-axis motion of the y-axis frame **136**. In an example, each of the x-axis and y-axis accelerometer sense electrodes **125**, **131** can include moving fingers coupled to one or more frame sections interdigitated with a set of stationary fingers fixed in position (e.g., to the via wafer **103**) using a respective anchor, such as anchors **126**, **132**.

X-Axis Accelerometer Response

FIG. **10** illustrates generally an example of a 3-axis accelerometer **1000** in sense motion in response to an x-axis acceleration, the 3-axis accelerometer including a single proof-mass, an anchor **106**, x-axis flexure bearings **133**, and an x-axis frame **135**.

In the presence of an acceleration along the x-axis, the proof-mass, the y-axis frame **136** and the x-axis frame **135** can move in unison with respect to the anchor **106**. The resulting motion can be detected using the x-axis accelerometer sense electrodes **125** located on opposite sides of the proof-mass, allowing differential measurement of deflections. In various examples, a variety of detection methods, such as capacitive (variable gap or variable area capacitors), piezoelectric, piezoresistive, magnetic or thermal can be used.

Y-Axis Accelerometer Response

FIG. **11** illustrates generally an example of a 3-axis accelerometer **1100** in sense motion in response to a y-axis acceleration, the 3-axis accelerometer including a single proof-mass, an anchor **106**, y-axis flexure bearings **134**, and a y-axis frame **136**.

In the presence of an acceleration along the y-axis, the y-axis flexure bearings **134** that connect the y-axis frame **136** to the x-axis frame **135** deflect and allow the y-axis frame **136** to move along the y-axis in unison with the proof-mass, while the x-axis frame remains stationary. The resulting motion can be detected using the y-axis accelerometer sense electrodes **131** located on opposite sides of the proof-mass, allowing differential measurement of deflections. In various examples, a variety of detection methods, such as capacitive (variable gap or variable area capacitors), piezoelectric, piezoresistive, magnetic or thermal can be used.

Z-Axis Accelerometer Response

FIG. **12** illustrates generally an example of a 3-axis accelerometer **1200** in sense motion in response to a z-axis acceleration, the 3-axis accelerometer including a single proof-mass **138**, an anchor, and z-axis flexure bearings **137**.

In the example of FIG. **12**, the x-axis flexure bearings **137** are located such that the axis that passes through the center of the beam is offset from the center of the proof-mass **138**. Thus, a mass imbalance is created, so that the portion of the mass that is located further from the pivot line generates a larger inertial moment than the portion located closer, rendering the proof-mass **138** sensitive to z-axis accelerations, deflecting torsionally out-of-plane about the pivot line. The x and y-axis flexure bearings **133**, **134** are designed to have high out-of-plane stiffness. Accordingly, they remain stationary during z-axis acceleration.

FIG. **13** illustrates generally an example of a system **1300** including via wafer electrode placement. In an example, z-axis accelerometer electrodes **140** can be placed on the via wafer **103** under the device layer **105**. The torsional response allows measurement of deflections differentially with only one layer of out-of-plane electrodes. In an example, a variety of detection methods such as capacitive (variable gap or variable area capacitors), piezoelectric, piezoresistive, magnetic or thermal can be employed.

FIG. **14** illustrates generally an example side view of a 3-axis accelerometer **1400** including a single proof-mass, an illustrative “pivot”, and z-axis accelerometer electrodes **140**.

3+3DOF

FIG. **15** illustrates generally an example of a 3+3-degrees-of-freedom (3+3DOF) inertial measurement unit (IMU) **200** (e.g., a 3-axis gyroscope and a 3-axis accelerometer), such as formed in a single plane of a device layer **105** of an IMU. In an example, the 3+3 DOF can include a 3-axis gyroscope **1505** and a 3-axis accelerometer **1510** on the same wafer.

In this example, each of the 3-axis gyroscope **1505** and the 3-axis accelerometer **1510** have separate proof-masses, though when packaged, the resulting device (e.g., chip-scale package) can share a cap, and thus, the 3-axis gyroscope **1505** and the 3-axis accelerometer **1510** can reside in the same cavity. Moreover, because the devices were formed at similar times and on similar materials, the invention significantly lowers the risk of process variations, reduces the need to separately calibrate the sensors, reduces alignment issues, and allows closer placement than separately bonding the devices near one another.

Further, there is a space savings associated with sealing the resulting device. For example, if a 100 um seal width is required, sharing the cap wafer and reducing the distance between devices allows the overall size of the resulting device to shrink Packaged separately, the amount of space required for the seal width could double.

In an example, die size can be reduced to 2.48×1.8 mm with a 100 um seal width.

Drive and Detection Frequencies

In an example, the drive mode and the three gyroscope sense modes can be located in the 20 kHz range. For open-loop operation, the drive mode can be separated from the sense-modes by a mode separation, such as 100 Hz to 500 Hz, which can determine the mechanical sensitivity of the gyroscopes. To increase sensitivity, the gyroscope operational resonant frequencies can be reduced if the vibration specifications of the application allow. If closed-loop sense operation is implemented, the mode separation can be reduced to increase mechanical sensitivity further.

Quadrature Error Reduction

FIG. **16** illustrates generally an example of the central suspension **111** at rest about an anchor **106**, the central suspension **111** including symmetric “C-beams” configured to locally cancel quadrature error. The primary source of quadrature error in micromachined gyroscopes is the DRIE sidewall angle errors, which result in deviation of the etch profile from a straight sidewall. If sidewalls have an angle error, the in-plane drive motion can also cause out-of-plane motion when the skew axis is along beam length. Thus, when skewed compliant beams are located on opposite sides of the drive motion, the resulting out-of-plane deflections cause quadrature error.

FIG. **17** illustrates generally an example of a portion of the central suspension **111** in drive motion. The central suspension **111** utilizes symmetric “C-beams” on each side of the anchor **106**. The out-of-plane motion caused by each C-beam on a side is cancelled out by its symmetric counterpart. Thus, the quadrature error induced on each beam can be locally cancelled.

Accelerometer Electrode Structure

FIG. **18** illustrates generally an example of an accelerometer electrode structure **1800** including an electrode stator frame **141** and a proof-mass frame **142** configured to support accelerometer sense electrodes (e.g., x-axis accelerometer sense electrodes **125**, etc.) including moving fingers interdigitated with stationary fingers configured to detect motion along one or more axes.

A first major side of the accelerometer electrode structure **1800** can be substantially bound by the electrode stator frame **141** fixed in position (e.g., to a via wafer **103**) using an anchor **126** and including a central platform **143** positioned substantially perpendicular to the electrode stator frame **141** and first and second outer branches **144**, **145** substantially parallel to at least a portion of the central platform **143**.

In an example, the electrode stator frame **141** and a first portion of the central platform **143** can surround and provide support for the anchor **126**. A second portion of the central platform, distal from the anchor **126**, can narrow, providing increased area for accelerometer sense electrodes (e.g., x-axis accelerometer sense electrodes **125**).

A second major side of the accelerometer electrode structure **1800**, substantially parallel to the first major side, can be substantially bound by the proof-mass frame **142** including first and second inner branches **148**, **149** substantially perpendicular to the proof-mass frame **142** and first and second outer branches **146**, **147** substantially parallel to the first or second inner branches **148**, **149**.

In the example of FIG. **18**, the first and second outer branches **146**, **147** of the proof-mass frame **142** can surround the first and second outer branches **144**, **145** of the electrode stator frame **141** on first and second minor sides of the accelerometer electrode **1800** (e.g., the top and bottom in FIG. **18**). In an example, to reduce proof-mass weight, the first and second outer branches **146**, **147** of the proof-mass frame **142** can be excluded.

FIG. **19** illustrates generally an example of an accelerometer electrode structure **1900** including an electrode stator frame **151** and a proof-mass frame **152** configured to support accelerometer sense electrodes (e.g., x-axis accelerometer sense electrodes **125**, etc.) including moving fingers interdigitated with stationary fingers configured to detect motion along one or more axes.

The present inventors have recognized, among other things, that shifting mass from the electrode stator frame **151** to the proof-mass frame **152** can improve the shock and vibration resistance of the accelerometer electrode structure **1900** or an associated inertial sensor. Further, the present inventors have recognized that providing a wider central platform **153** can allow independent or asymmetric anchor **126** placement on each or either side of the associated inertial sensor to, for example, to compensate for die deformation, such as from packaging stress, to improve temperature performance, etc.

Similar to the example illustrated in FIG. **18**, a first major side of the accelerometer electrode structure **1900** can be substantially bound by an electrode stator frame **151** fixed in position (e.g., to a via wafer **103**) using the anchor **126** and including a central platform **153** positioned substantially perpendicular to the electrode stator frame **151** and first and second inner branches **154**, **155** substantially parallel to at least a portion of the central platform **153**.

In an example, the electrode stator frame **151** and the central platform **153** can surround and provide support for the anchor **126**. In contrast to the example illustrated in FIG. **18**, the central platform **152** of FIG. **19** can be wider than the central platform **142** of FIG. **18**, providing a wider platform to locate the anchor **126**, in certain examples, allowing independent or adjustable anchor **126** positions on each or either side of the inertial sensor. In certain examples, independent or adjustable anchor positions for one or both sides of the inertial sensor can improve temperature performance of the inertial sensor, depending on, for example, the position of the inertial sensor on a die.

A second major side of the accelerometer electrode structure **1900**, substantially parallel to the first major side, can be substantially bound by a proof-mass frame **152** including first and second inner branches **158**, **159** substantially perpendicular to the proof-mass frame **152** and first and second outer branches **156**, **157** substantially parallel to the first or second inner branches **158**, **159**.

In the example of FIG. **19**, the first and second inner branches **154**, **155** of the electrode stator frame **151** and the first and second inner branches **158**, **159** of the proof-mass frame **152** can be positioned closer to the central platform **153** than the example illustrated in FIG. **18**. In an example, shifting these branches closer to the central platform **153** can allow a shift of a portion of the electrode mass to the proof-mass side of the accelerometer electrode structure **1900**, minimizing the mass of the electrode stator **151** to improve shock or vibration resistance or to increase the lower or lowest resonant frequencies of the capacitive accelerometer sense electrodes, such as illustrated in FIG. **24**.

FIG. **20** illustrates generally an example of an accelerometer electrode structure **2000**, such as that illustrated in the example of FIG. **18**. In this example, the electrode stator frame **141** and the proof-mass frame **142** are separated, separately illustrating moving fingers **160** decoupled from stationary fingers **161**.

FIG. **21** illustrates generally an example of an accelerometer electrode structure **2100**, such as that illustrated in the example of FIG. **19**. In this example, the electrode stator frame **151** and the proof-mass frame **152** are separated, separately illustrating moving fingers **162** decoupled from stationary fingers **163**. Although the central platform **153** illustrated in FIGS. **19** and **21** is wider than the central platform **143** illustrated in FIGS. **18** and **20**, the reduced mass electrode stator frame **151** can provide for an additional sense electrodes or additional sense electrode area.

FIG. **22** illustrates generally an example of a decoupled left and right accelerometer electrode structure **2200** including a left anchor **126**A, a left central platform **153**A, a right anchor **126**B, and a right central platform **153**B. In this example, the left and right anchors **126**A, **126**B are positioned asymmetrically to optimize or improve temperature performance. In certain examples, the left and right anchors **126**A, **126**B can be positioned independently or asymmetrically to compensate for non-centered placement on the die or asymmetric die deformation, such as from packaging stress. In certain examples, placement of the anchors towards the stator side versus the proof-mass side can be specifically configured to compensate for temperature performance, to adjust for offset inertial sensor placement on a die, to adjust for inertial sensor packaging, or one or more other factors.

FIG. **23** illustrates generally an example of a lowest out-of-plane resonant mode of an electrode stator frame **141**, such as that illustrated in the examples of FIGS. **18** and **20**.

FIG. **24** illustrates generally an example of a lowest out-of-plane resonant mode of an electrode stator frame **151**, such as that illustrated in the examples of FIGS. **19** and **21**.

The resonant modes of FIGS. **23** and **24** illustrate generally that the lowest out-of-plane resonant mode of the electrode stator frame **151** of the example of FIG. **24** is higher than the lowest out-of-plane resonant mode of the electrode stator frame **141** of the example of FIG. **23**.

Additional Notes and Examples

In Example 1, an inertial sensor includes a single proof-mass formed in an x-y plane of a device layer, the single proof-mass including a single, central anchor configured to suspend the single proof-mass above a via wafer, first and second electrode stator frames formed in the x-y plane of the device layer on respective first and second sides of the inertial sensor, the first and second electrode stator frames symmetric about the single, central anchor, and each separately including a central platform and an anchor configured to fix the central platform to the via wafer, wherein the anchors for the first and second electrode stator frames are asymmetric along the central platforms with respect to the single, central anchor.

In Example 2, the first and second electrode stator frames of Example 1 optionally includes first and second inner branches and a plurality of stationary fingers coupled to the first and second inner branches.

In Example 3, the first inner branch of any one or more of Examples 1-2 is substantially parallel to the second inner branch.

In Example 4, the first and second inner branches of the first and second electrode stator frames are substantially parallel to the central platforms of the first and second electrode stator frames.

In Example 5, the central platforms of the first and second electrode stator frames of any one or more of Examples 1-4 are optionally symmetric about the single, central anchor.

In Example 6, any one or more of Examples 1-5 optionally includes first and second proof-mass frames formed in the x-y plane of the device layer, each coupled to the single proof-mass and including first and second inner branches about and substantially parallel to the central platform, first and second outer branches, and a plurality of moving fingers coupled to the first and second inner and outer branches.

In Example 7, the first and second electrode stator frames of any one or more of Examples 1-6 optionally have a first mass, wherein the first and second proof-mass frames of any one or more of Examples 1-6 optionally have a second mass, and wherein the first mass is optionally less than the second mass.

In Example 8, at least a portion of the plurality of stationary fingers of any one or more of Examples 1-7 are optionally interdigitated with at least a portion of the plurality of moving fingers.

In Example 9, the stationary fingers of any one or more of Examples 1-8 are optionally substantially perpendicular to the first and second inner branches of the first and second electrode stator frames, wherein the moving fingers are optionally substantially perpendicular to the first and second inner and outer branches of the first and second proof-mass frames.

In Example 10, any one or more of Examples 1-9 optionally include a single proof-mass 3-axis accelerometer including the single proof-mass and separate x, y, and z-axis flexure bearings, wherein the x and y-axis flexure bearings are optionally symmetric about the single, central anchor and the z-axis flexure is optionally not symmetric about the single, central anchor.

In Example 11, the 3-axis accelerometer of any one or more of Examples 1-10 optionally includes in-plane x and y-axis accelerometer sense electrodes symmetric about the single, central anchor and out-of-plane z-axis accelerometer sense electrodes, wherein the in-plane x-axis accelerometer sense electrodes optionally include the first and second electrode stator frames.

In Example 12, any one or more of Examples 1-11 optionally includes a single proof-mass 3-axis gyroscope formed in the x-y plane adjacent the 3-axis accelerometer, the single proof-mass 3-axis gyroscope including a main proof-mass section suspended about a single, central anchor, the main proof-mass section including a radial portion extending outward towards an edge of the 3-axis gyroscope, a central suspension system configured to suspend the 3-axis gyroscope from the single, central anchor, and a drive electrode including a moving portion and a stationary portion, the moving portion coupled to the radial portion, wherein the drive electrode and the central suspension system are configured to oscillate the 3-axis gyroscope about a z-axis normal to the x-y plane at a drive frequency.

In Example 13, any one or more of Examples 1-12 optionally includes a cap wafer bonded to a first surface of the device layer, wherein the via wafer is optionally bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are optionally configured to encapsulate the single proof-mass 3-axis gyroscope and the single proof-mass 3-axis accelerometer in the same cavity.

In Example 14, the single, central anchor of any one or more of Examples 1-13 is optionally not centered on the via wafer, wherein the anchors for the first and second electrode stator frames are optionally asymmetric along the central platforms with respect to the single, central anchor to improve temperature performance associated with thermal deformation.

In Example 15, any one or more of Examples 1-14 optionally includes a single proof-mass formed in an x-y plane of a device layer, the single proof-mass including a single, central anchor configured to suspend the single proof-mass above a via wafer, x-axis flexure bearings symmetric about the single, central anchor, a first proof-mass frame, a first electrode stator frame on a first side of the single, central anchor, the first electrode stator frame including a first central platform, first and second inner branches, a plurality of stationary fingers coupled to the first and second inner branches, and a first anchor configured to fix the first electrode stator frame to the via wafer at a first position along the first central platform, and a second electrode stator frame on a second side of the single, central anchor, the second electrode stator frame including a second central platform, third and fourth inner branches, a plurality of stationary fingers coupled to the third and fourth inner branches, and a second anchor configured to fix the second electrode stator frame to the via wafer at a second position along the second central platform, wherein the first position along the first central platform and the second position along the second central platform are asymmetric with respect to the single, central anchor.

In Example 16, the first and second electrode stator frames of any one or more of Examples 1-15 are optionally symmetric about the single, central anchor.

In Example 17, the inertial sensor of any one or more of claims 1-16 optionally include first and second proof-mass frames formed in the x-y plane of the device layer, each coupled to the single proof-mass and including first and second inner branches about and substantially parallel to the first and second central platforms, first and second outer branches, and a plurality of moving fingers coupled to the first and second inner and outer branches. At least a portion of the plurality of stationary fingers of any one or more of Examples 1-16 optionally are interdigitated with at least a portion of the plurality of moving fingers.

In Example 18, a method can include suspending a single proof-mass formed in an x-y plane of a device layer above a via wafer using a single, central anchor, asymmetrically, with respect to the single, central anchor, anchoring first and second electrode stator frames along central platforms of the first and second electrode stator frames formed in the x-y plane of the device layer to the via wafer, wherein the first and second electrode stator frames are symmetric about the single, central anchor, and detecting acceleration between the single proof-mass and the first and second electrode stator frames.

In Example 19, the suspending the single proof-mass of any one or more of Examples 1-18 optionally includes suspending a single proof-mass 3-axis accelerometer having symmetric x and y-axis flexure bearings about the single, central anchor and asymmetric z-axis flexure bearings about the single, central anchor.

In Example 20, the asymmetrically anchoring the first and second electrode stator frames along the central platforms with respect to the single, central anchor of any one or more of Examples 1-19 optionally includes to compensate for package deformation and improve temperature performance of an inertial sensor associated with the single proof-mass.

Example 21 can include, or can optionally be combined with any portion or combination of any portions of any one or more of Examples 1-20 to include, subject matter that can include means for performing any one or more of the functions of Examples 1-20, or a machine-readable medium including instructions that, when performed by a machine, cause the machine to perform any one or more of the functions of Examples 1-20.

The above detailed description includes references to the accompanying drawings, which form a part of the detailed description. The drawings show, by way of illustration, specific embodiments in which the invention can be practiced. These embodiments are also referred to herein as "examples." Such examples can include elements in addition to those shown or described. However, the present inventors also contemplate examples in which only those elements shown or described are provided. Moreover, the present inventors also contemplate examples using any combination or permutation of those elements shown or described (or one or more aspects thereof), either with respect to a particular example (or one or more aspects thereof), or with respect to other examples (or one or more aspects thereof) shown or described herein.

All publications, patents, and patent documents referred to in this document are incorporated by reference herein in their entirety, as though individually incorporated by reference. In the event of inconsistent usages between this document and those documents so incorporated by reference, the usage in the incorporated reference(s) should be considered supplementary to that of this document; for irreconcilable inconsistencies, the usage in this document controls.

In this document, the terms "a" or "an" are used, as is common in patent documents, to include one or more than one, independent of any other instances or usages of "at least one" or "one or more." In this document, the term "or" is used to refer to a nonexclusive or, such that "A or B" includes "A but not B," "B but not A," and "A and B," unless otherwise indicated. In the appended claims, the terms "including" and "in which" are used as the plain-English equivalents of the respective terms "comprising" and "wherein." Also, in the following claims, the terms "including" and "comprising" are open-ended, that is, a system, device, article, or process that includes elements in addition to those listed after such a term in a claim are still deemed to fall within the scope of that claim. Moreover, in the following claims, the terms "first," "second," and "third," etc. are used merely as labels, and are not intended to impose numerical requirements on their objects.

Method examples described herein can be machine or computer-implemented at least in part. Some examples can include a computer-readable medium or machine-readable medium encoded with instructions operable to configure an electronic device to perform methods as described in the above examples. An implementation of such methods can include code, such as microcode, assembly language code, a higher-level language code, or the like. Such code can include computer readable instructions for performing various methods. The code may form portions of computer program products. Further, the code can be tangibly stored on one or more volatile or non-volatile tangible computer-readable media, such as during execution or at other times. Examples of these tangible computer-readable media can include, but are not limited to, hard disks, removable magnetic disks, removable optical disks (e.g., compact disks and digital video disks), magnetic cassettes, memory cards or sticks, random access memories (RAMs), read only memories (ROMs), and the like.

The above description is intended to be illustrative, and not restrictive. For example, the above-described examples (or one or more aspects thereof) may be used in combination with each other. Other embodiments can be used, such as by one of ordinary skill in the art upon reviewing the above description. The Abstract is provided to comply with 37 C.F.R. §1.72(b), to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims. Also, in the above Detailed Description, various features may be grouped together to streamline the disclosure. This should not be interpreted as intending that an unclaimed disclosed feature is essential to any claim. Rather, inventive subject matter may lie in less than all features of a particular disclosed embodiment. Thus, the following claims are hereby incorporated into the Detailed Description, with each claim standing on its own as a separate embodiment, and it is contemplated that such embodiments can be combined with each other in various combinations or permutations. The scope of the invention should be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

What is claimed is:

1. An inertial sensor, comprising:

a single proof-mass formed in an x-y plane of a device layer, the single proof-mass including a single, central anchor configured to suspend the single proof-mass above a via wafer;

first and second electrode stator frames formed in the x-y plane of the device layer on respective first and second sides of the inertial sensor, the first and second electrode stator frames symmetric about the single, central anchor, and each separately including:

a central platform; and

an anchor configured to fix the central platform to the via wafer;

wherein the anchors for the first and second electrode stator frames are positioned asymmetrically along the central platforms with respect to the single, central anchor.

2. The inertial sensor of claim **1**, wherein the first and second electrode stator frames include:

first and second inner branches; and

a plurality of stationary fingers coupled to the first and second inner branches.

3. The inertial sensor of claim **2**, wherein the first inner branch is substantially parallel to the second inner branch.

4. The inertial sensor of claim **3**, wherein the first and second inner branches of the first and second electrode stator frames are substantially parallel to the central platforms of the first and second electrode stator frames.

5. The inertial sensor of claim **4**, wherein the central platforms of the first and second electrode stator frames are symmetric about the single, central anchor.

6. The inertial sensor of claim **2**, including:

first and second proof-mass frames formed in the x-y plane of the device layer, each coupled to the single proof-mass and including:

first and second inner branches about and substantially parallel to the central platforms;

first and second outer branches; and

a plurality of moving fingers coupled to the first and second inner and outer branches.

7. The inertial sensor of claim **6**, wherein the first and second electrode stator frames have a first mass, wherein the first and second proof-mass frames have a second mass, and wherein the first mass is less than the second mass.

8. The inertial sensor of claim **6**, wherein at least a portion of the plurality of stationary fingers are interdigitated with at least a portion of the plurality of moving fingers.

9. The inertial sensor of claim **6**, wherein the stationary fingers are substantially perpendicular to the first and second inner branches of the first and second electrode stator frames; and

wherein the moving fingers are substantially perpendicular to the first and second inner and outer branches of the first and second proof-mass frames.

10. The inertial sensor of claim **1**, including:

a single proof-mass 3-axis accelerometer including the single proof-mass and separate x, y, and z-axis flexure bearings; and

wherein the x and y-axis flexure bearings are symmetric about the single, central anchor and the z-axis flexure is not symmetric about the single, central anchor.

11. The inertial sensor of claim **10**, wherein the 3-axis accelerometer includes in-plane x and y-axis accelerometer sense electrodes symmetric about the single, central anchor and out-of-plane z-axis accelerometer sense electrodes; and

wherein the in-plane x-axis accelerometer sense electrodes include the first and second electrode stator frames.

12. The inertial sensor of claim **11**, including:

a single proof-mass 3-axis gyroscope formed in the x-y plane adjacent the 3-axis accelerometer, the single proof-mass 3-axis gyroscope including:

a main proof-mass section suspended about a single, central anchor, the main proof-mass section including a radial portion extending outward towards an edge of the 3-axis gyroscope;

a central suspension system configured to suspend the 3-axis gyroscope from the single, central anchor; and

a drive electrode including a moving portion and a stationary portion, the moving portion coupled to the radial portion, wherein the drive electrode and the central suspension system are configured to oscillate the 3-axis gyroscope about a z-axis normal to the x-y plane at a drive frequency.

13. The apparatus of claim **11**, including:

a cap wafer bonded to a first surface of the device layer; and

wherein the via wafer is bonded to a second surface of the device layer, wherein the cap wafer and the via wafer are configured to encapsulate the single proof-mass 3-axis gyroscope and the single proof-mass 3-axis accelerometer in the same cavity.

14. The inertial sensor of claim **1**, wherein the single, central anchor is not centered on the via wafer; and

wherein the anchors for the first and second electrode stator frames are asymmetric along the central platforms with respect to the single, central anchor to improve temperature performance associated with thermal deformation.

15. An inertial sensor, comprising:

a single proof-mass formed in an x-y plane of a device layer, the single proof-mass including:

a single, central anchor configured to suspend the single proof-mass above a via wafer;

x-axis flexure bearings symmetric about the single, central anchor;

a first proof-mass frame;

a first electrode stator frame on a first side of the single, central anchor, the first electrode stator frame including:

a first central platform;

first and second inner branches;

a plurality of stationary fingers coupled to the first and second inner branches; and

a first anchor configured to fix the first electrode stator frame to the via wafer at a first position along the first central platform; and

a second electrode stator frame on a second side of the single, central anchor, the second electrode stator frame including:

a second central platform;

third and fourth inner branches;

a plurality of stationary fingers coupled to the third and fourth inner branches; and

a second anchor configured to fix the second electrode stator frame to the via wafer at a second position along the second central platform; and

wherein the first position along the first central platform and the second position along the second central platform are asymmetric with respect to the single, central anchor.

16. The inertial sensor of claim **15**, wherein the first and second electrode stator frames are symmetric about the single, central anchor.

17. The inertial sensor of claim **16**, including:

first and second proof-mass frames formed in the x-y plane of the device layer, each coupled to the single proof-mass and including:

first and second inner branches about and substantially parallel to the first and second central platforms;

first and second outer branches; and

a plurality of moving fingers coupled to the first and second inner and outer branches; and

wherein at least a portion of the plurality of stationary fingers are interdigitated with at least a portion of the plurality of moving fingers.

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